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RESEARCH MEMORANDUM

INVESTIGATION OF ANNULAR LIQUID FLOW WITH COCURRENT
AIR FLOW IN HORIZONTAL TUBES

By George R. Kinney and Andrew E. Abramson

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NATIONAL ADVISORY COMMITTEE
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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INVESTIGATION OF ANNULAR LIQUID FLOW WITH COCURRENT

AIR FLOW IN HORIZONTAL TUBES

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SUMMARY

Visual observations and flow analyses were made of annular liquid flow with cocurrent air flow in 2- and 4-inch-diameter horizontal transparent tubes. The experiments were conducted with air mass velocities from 30.6 to 108 pounds per second per square foot, air temperatures of 80°, 475°, and 800° F, and Reynolds numbers from 410,000 to 2,900,000. The liquid flows consisted of water, water-detergent solutions, and aqueous ethylene-glycol solutions (which varied liquid viscosity and surface tension) at flow rates of 0.027 to 0.270 pound per second per foot of tube circumference (0.3 to 21 percent of the air flows).

The surface velocity of the annular liquid film varied from about 10 to 35 feet per second; corresponding liquid-film thicknesses were approximately 0.005 to 0.0005 inch. The surface of the liquid film was observed to be relatively smooth at low liquid flows, which corresponded to the liquid annulus being in the flow region where viscous forces are appreciable. A definite disturbance of the liquid-film surface was observed at higher liquid flows, which corresponded to the liquid annulus being in the flow region where turbulent forces are predominant. The liquid flow per circumferential length at which liquid-flow disturbances initially occurred increased with increased liquid viscosity, increased slightly with decreased liquid surface tension, and did not vary appreciably with changes of air mass velocity. Liquid-flow disturbances had different appearances with different air mass velocities, liquid viscosities, and liquid surface tensions; in general, the size and the number of disturbances varied.

For film-cooling applications, the presence of liquid-flow disturbances reduces the cooling effectiveness of the liquid because of higher heat transfer between gas and liquid and loss of liquid to the hot gas stream. The approximate liquid flow at which the liquid-film-surface disturbances initially occur can be predicted.

INTRODUCTION

A general investigation of liquid film cooling is being conducted at the NACA Lewis laboratory to determine the feasibility of its use where high heat-flux densities are encountered and to obtain correlations of experimental data that will allow predictions of film-coolant requirements for specific cooling problems.

Preliminary film-cooling experiments (reference 1) were conducted with hot air flows to determine the cooling effectiveness of water films on the inner surface of a straight tube. The relation between liquid-cooled length and coolant flow for given gas-stream conditions was non-linear; the effectiveness of a given amount of coolant decreased with increased coolant flow. This result indicated an increase in heat transfer and mixing between the hot gas and liquid film with increased coolant flow probably caused by changes in the flow characteristics of the coolant. A complete analysis and correlation of the heat-transfer data were not obtained because of this unknown effect, and information on the annular flow of liquids in a tube with cocurrent gas flow was therefore needed.

Investigations of two-phase, two-component flow have been conducted by various investigators and a summary of this work is contained in references 2 and 3. Visual observations of flow characteristics and pressure-drop determinations were made with different flows and flow ratios of the liquid and gas. The flows and flow ratios for these investigations, however, are considerably out of the range encountered in the film-cooling experiments.

An investigation was therefore conducted at the Lewis laboratory with liquid films in cocurrent flow with a gas for the flow ranges encountered in film cooling in order to: (a) determine the flow characteristics of the annular liquid flow for various gas-stream conditions, liquid properties, and physical dimensions of the test section; (b) correlate the observed liquid-flow characteristics with the flow variables; and (c) relate the liquid-flow characteristics to the change in cooling effectiveness encountered in the film-cooling experiments.

The experiments were conducted with 2- and 4-inch-diameter transparent tubes with air mass velocities from 30.6 to 108 pounds per second per square foot, air temperatures of 80°, 475°, and 800° F, Reynolds numbers from 410,000 to 2,900,000, and liquid flows from 0.027 to 0.270 pound per second per foot of tube circumference (0.3 to 21 percent of the air flows). Water, water-detergent solutions, and aqueous ethylene-glycol solutions (which varied viscosity and surface tension) were used as the liquids. Visual observations were made of the

flowing liquids with the aid of stroboscopic light. Photographs and high-speed motion pictures of the flows were obtained.

APPARATUS

Flow System

The flow system (fig. 1) is the same as that used in reference 1, except for the test sections. It consists essentially of three parts: (1) source of air at a uniform temperature, (2) test section, and (3) expansion and exhaust system. The air source consisted of the air supply at a pressure of 40 pounds per square inch gage, a surge chamber, a jet-engine combustor, a mixing section with orifice- and target-mixing baffles, and a calming chamber 12 inches in diameter. Test sections of 2- and 4-inch diameter were used. They consisted of an Inconel approach section 40 inches long, a liquid injector, and a transparent tube 48 inches long. The transparent tube fit into a packed housing that allowed for expansion of the apparatus, and the exhaust section contained a series of water sprays to quench hot air; this section was connected to the laboratory exhaust system. The assembly was supported at the surge chamber, by roller stands located upstream and downstream of the test section, and by a ring stand at the liquid injector.

Liquid-Injection System

The liquid-injection system was also the same as described in reference 1. It consisted of supply reservoir, filters, positive-displacement pump, adjustable pressure regulators (which controlled flow), rotameters, and liquid injectors (fig. 2).

The two liquid injectors were of similar construction. They consisted of a metal ring with slots milled into the inner surface about the circumference. The 2- and 4-inch-diameter liquid injectors had 60 and 90 slots, respectively. Holes 0.013 inch in diameter were drilled through the ring into each of the slots. A liner of porous wire cloth fit inside the metal ring over the slots. A housing, which provided a supply annulus for the liquid, fit over the ring. The liquid supplied to the annulus flowed through the small holes into the slots and then through the porous-cloth liner onto the surface. The small holes metered the flow into each slot, thus providing a uniform distribution of the flow about the circumference. The slots spread the liquid flow over a large area, thereby reducing the flow velocity. As the liner was very porous, it did not restrict the flow but provided a

surface onto which the liquid flowed at low velocity. The air flow over the surface of the injector carried the liquid downstream along the inner surface of the transparent tube.

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Transparent Tubes

Two 4-inch-diameter transparent tubes were used during the experiments, one made of pyrex and the other, of Lucite. Both tubes were 48 inches long and 1/4 inch thick and were sealed to an aluminum adapter by means of a flange; the adapter was sealed to the liquid injector. The other end of the tube fit into an expansion slip joint. The 2-inch-diameter transparent tube was Lucite and its construction and length were the same as those of the 4-inch-diameter tubes.

Instrumentation

Flow rate. - Air flow was measured within ± 250 pounds per hour (1 to 2 percent of the air flows) by means of an orifice conforming to standard A.S.T.M. specifications and a differential water manometer. The liquid flow was measured by means of rotameters within ± 5 pounds per hour (1 to 4 percent of flows used).

Temperature. - Temperatures were measured by means of chromel-alumel thermocouples and a self-balancing potentiometer. Air temperature was measured within $\pm 10^{\circ}$ F using a rake of four thermocouples in the approach section, 3 inches upstream of the liquid injector. Liquid temperature was measured within $\pm 5^{\circ}$ F by means of a thermocouple in the liquid-supply annulus of the injector.

Liquid-flow disturbance. - A stroboscopic light was placed on one side facing the transparent tube and observations of the liquid film were made looking into the tube from the opposite side. The timing of the stroboscopic light was adjusted for optimum visual clarity of the disturbances on the liquid film.

Shadowgraph pictures of the liquid film were obtained using a microflash light source on one side of the transparent tube, suitable condensing lenses, and a camera on the opposite side of the tube. The camera was focused on the liquid film surface nearer to it. High-speed motion pictures of the liquid flow were obtained using flood lamps on one side of the transparent tube and a high-speed camera on the opposite side. The high-speed camera reached a speed of 2000 frames per second and a timing mark was imposed on the film at 1/1000-second intervals.

An optical instrument was devised to measure the thickness of the liquid films during the experiments. The instrument consisted of a mechanism for focusing a point light source on the inner surface of the tube and on the surface of the liquid film. Measurement of the difference in position of the focusing lens for focusing on the two surfaces enabled determination of the distance between the surfaces. The instrument was calibrated using thin glass plates, and thickness measurements as small as 0.005 inch were possible.

PROCEDURE

An air flow was established through the test section. Ambient air was used for most of the experiments; when hot air was used, the air was heated by burning gasoline in the combustor. Liquid was introduced about the circumference of the tube at the injector and the liquid flow was increased until the inner surface of the transparent tube was covered with a film of liquid. The liquid-film surface was observed using the stroboscopic light, and as the liquid flow was increased in small increments a description of the surface was recorded. The procedure was continued through the range of liquid flow investigated at each of the flow conditions.

The liquid-film surface became gradually disturbed as liquid flow was increased. A transition region of liquid flow from relatively smooth to definitely disturbed liquid film was determined for most of the liquids from visual observations by at least two independent observers. The agreement between observers was within about 10 percent and an average of their results was used. As a check on visual observations, shadowgraph and high-speed motion pictures were taken of the liquid film for various flow conditions.

The flow conditions covered the following ranges:

Air mass velocity, lb/(sec)(sq ft)	30.6 - 108
Air temperature, $^{\circ}$ F	80,475,800
Liquid flow, lb/(sec)(ft)	0.027 - 0.270

Water containing various quantities of detergent (aerosol) and water - ethylene-glycol solutions were used in the experiments. The

following table lists the liquids used and their properties at the various temperatures during the experiments:

Liquid	Temperature (°F)	Absolute viscosity (lb-sec)/(sq ft)	Surface tension (dynes/cm)
Water	80	1.84×10^{-5}	72
Water	210	.606	57
Water and 0.004-percent detergent	80	1.84	55
Water and 0.025-percent detergent	80	1.84	45
Water and 0.050-percent detergent	80	1.84	41
Water and 0.095-percent detergent	80	2.05	36
Water and 0.150-percent detergent	80	2.07	33
Water and 12-percent ethylene glycol	80	2.72	70
Water and 53-percent ethylene glycol	80	7.74	62
Water and 98-percent ethylene glycol	80	31.4	54

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RESULTS

Velocity and Thickness of Liquid Films

The liquid films established on the inner surface of the transparent tube were very thin for the range of test conditions. Computed values of the liquid-film thickness were from 0.005 to 0.0005 inch with corresponding surface velocities of the liquid film from 10 to 35 feet per second. The symbols and the method used for calculating the liquid-film thickness or velocity are given in appendixes A and B, respectively. The velocity of the surface disturbances was measured from the high-speed motion pictures taken at various conditions. These values agreed favorably with the calculated surface velocity of the liquid film for the same conditions.

Experimentally determined velocities of surface disturbances and corresponding thicknesses of liquid films are shown in the following table:

Air mass velocity (lb/(sec)(sq ft))	Water flow (lb/(sec)(ft))			
	0.040		0.123	
	Disturbance velocity (ft/sec)	Film thickness (in.)	Disturbance velocity (ft/sec)	Film thickness (in.)
44.5	17.5	0.002	21	0.005
108	----	-----	30	.003

The effect of gravity on the liquid film, which would be to decrease the film thickness in the upper portions of the horizontal tubes, was probably inappreciable with the gas velocities and coolant flows investigated, as was indicated in the film-cooling experiments of reference 2. Attempts at direct measurement of the film thickness on the side of the tube where the observations were made, using the optical device described in the apparatus, showed film thicknesses to be less than the sensitivity of the instrument (0.005 inch), which substantiates the order of magnitude of the computed values.

Description of Water-Film Disturbances

Observations, using stroboscopic light, of water films on the inside surface of transparent tubes revealed changes in the appearance of the flow for different water flows. With constant air-stream conditions, the water flow appeared essentially smooth at low water flows; whereas there were disturbances having the appearance of waves on the water surface at higher water flows. The change in the appearance of the water flow occurs gradually as the water flow increases; figure 3 shows shadowgraph pictures of the flow for increasing water flows at two air flows. The photographs are arranged to show three regions involved in the changing appearance of the water flow as the flow increases: (1) smooth flow (no appreciable disturbance); (2) transition from small traces of disturbance to appreciable and consistent clearly visible disturbances; and (3) increasing number and magnitude of disturbances. Although there was a gradual change from undisturbed to disturbed flow, liquid flows that define the transition region from an undisturbed to an appreciably disturbed surface for given flow conditions could be determined by two or more observers with good agreement.

The degree of disturbance continues to increase with increased liquid flow after the transition region.

Effect of Flow Variables on Liquid-Film Characteristics

Experiments were conducted to determine the effect of several variables on the values of liquid flow per circumferential length over which the flow transition occurred and on the appearance of the surface. The variables investigated were air mass velocity, tube diameter, air temperature, liquid viscosity, and liquid surface tension. The values of liquid flow per circumferential length defining the transition region for the different flow conditions are given in tables I and II.

Effect of air mass velocity. - The liquid flows defining the transition region with water are given in table I for different air mass velocities at ambient temperature using three different transparent tubes. The water flows per circumferential length over which the flow transition occurred for the air mass velocities investigated did not appreciably change. The shadowgraph pictures of the water flows (figs. 3(a) and 3(b)) show, however, that the disturbances had different appearances with the different air mass velocities; visual observations using stroboscopic light gave the same result. The disturbances at the higher air mass velocity appear smaller and more numerous than those at the lower one. A comparison of the transition regions using the pyrex and Lucite tubes (table I) shows that the region for the Lucite tube starts at a flow about 25 percent lower than that for the pyrex tube. Otherwise the region was the same for the different tube surfaces and the disturbances had the same appearance for corresponding air mass velocities.

Effect of tube diameter. - The transition region for several air mass velocities using 4- and 2-inch-diameter Lucite tubes is also shown in table I. The results show no appreciable difference in the transition region (liquid flow per circumferential length) for the two tube diameters and the disturbances had the same appearance for corresponding air mass velocities.

Effect of air temperature. - Significant information on the effect of air temperature on the transition region could not be obtained because water-flow rates in this region were too small to form a liquid film along the entire length of the tube at high air temperatures and thus prevent overheating of the tube. A determination of the transition region was made, however, at an air temperature of 475° F at a position in the tube 2 feet downstream of the water injection; transition occurred at flows between 0.047 and 0.063 pound per second per foot,

which is of the same order of magnitude as that for ambient air. Results obtained with negligible evaporation of the water film at ambient air temperature cannot be compared with results obtained with appreciable evaporation at elevated air temperature because of the continually changing water-flow rate of the film along the length of the tube in the case of appreciable evaporation. Furthermore, an appreciable temperature gradient may occur in the film with the elevated air temperature; the temperature and hence properties of the water were therefore unknown.

Although the transition region was not determined at high air temperatures, flow disturbances accompanying high rates of water flow were observed. For example, figure 4 shows shadowgraph pictures of the water flow for air temperatures of 80° and 800° F for the same air flow. The pictures indicate, as did visual observations, that the disturbances had the same appearance at the different air-stream temperatures; apparently there is no boiling or appreciable effect on the liquid-film surface due to vaporization.

Effect of liquid viscosity. - Variation of liquid viscosity and surface tension was obtained by using water - ethylene-glycol solutions and water-detergent solutions. The properties of the solutions that were used are listed in the table in the "Procedure" section.

The liquid-flow disturbances using aqueous glycol solutions to vary viscosity were observed to differ from those using water. The disturbances became less wave-like in appearance, smaller in size, and less distinct with increased viscosity. Figure 5 shows shadowgraph pictures of the flow of a 53-percent glycol-water solution at various liquid flows and indicates that the development of the surface disturbances is very gradual with increased liquid flow. Glycol-water solutions varying from 12- to 98-percent glycol were investigated by visually observing the occurrence of the disturbances with the aid of stroboscopic light. Although it was difficult to define a transition region as with water, the increase of disturbance with liquid flow was observed with each liquid. As viscosity was increased by the use of glycol, higher liquid flows were required before appreciable disturbances showed; this effect was greater than could be attributed to the relatively small decrease in surface tension with increased glycol.

Effect of surface tension. - In table II are shown an increase in the liquid flows for the start of the transition region and an increase in the magnitude of the transition-flow region for decreases in liquid surface tension. The transition region for the 0.095-percent detergent solution (surface tension, 50 percent of that for water) starts at a liquid flow about 20 percent higher than that for water and the magnitude of the transition flow region is about twice as large as that for

water. Visual observations of the flow of water detergent for which the surface tension varied between that of water and 50 percent that of water showed the following trends with increased flow rate: (1) In the region of low liquid-flow rate corresponding to the smooth-flow region for water, the flow had no individual disturbances but had the appearance of having small areas of roughened surface; these areas disappeared with increased flow rate until the surface was essentially smooth; and (2) with further increase of the flow rate, disturbances similar to those occurring with water appeared and the increase of disturbance was similar to that occurring with water. The flow of a liquid having a higher concentration of detergent, which resulted in a surface tension less than 50 percent of that for water, showed the following trends with increased flow rate: (1) At low liquid flows, small areas of roughened surface occurred that were similar to those for the other detergent solutions; these disturbances, however, did not disappear with increased liquid flow but increased in size and intensity with the entire surface becoming covered with the disturbance; and (2) no disturbances appearing as waves were detected over the flow range investigated.

Relation Between Disturbances and Flow Conditions

By analysis, the surface disturbances or turbulence of the liquid film was found to originate when the thickness of the liquid film enters a flow region where turbulent forces predominate over viscous forces. Plots of the generalized velocity distribution for fully developed flow in smooth tubes, as given in references 4 and 5, are shown in figure 6 and this distribution is assumed applicable to the liquid film. The flow regions where the viscous or turbulent forces predominate are defined by the value of the wall-distance parameter y^+ . Viscous forces predominate in the laminar layer ($y^+ < 3$); turbulent forces, in the turbulent core ($y^+ > 30$); and both laminar and turbulent forces are present in the intermediate region ($3 < y^+ < 30$) (references 4 and 5).

For the purposes of this investigation, it is convenient to place the results in terms of w^+ , a flow-rate parameter, because the flow of the liquid was measured for each run. This flow-rate parameter, which is the integral of the curve of y^+ against u^+ (fig. 6), is derived in appendix C.

Visual results. - Values of the flow-rate parameter w^+ were calculated for the median liquid flows defining the transition region as listed in tables I and II; the viscosity of the liquids at 80° F (temperature when introduced into tube) was used. The corresponding

values of y^+ were obtained from figure 7, which is a graphical integration of the curve of figure 6 for various values of y^+ (appendix C). These values are plotted on the generalized velocity distribution of figure 6. The highest and lowest values of y^+ defining the transition region as obtained from tables I and II are also shown on figure 6 by dotted lines and the data indicate that the observed transition region for the various conditions occurred over the region of $y^+ = 12$ to $y^+ = 21$. The previously defined flow regions as shown on figure 3 may be associated with figure 6 as follows: At values of $y^+ < 12$, the liquid film appears relatively smooth. In the region $12 < y^+ < 21$, a surface disturbance develops on the liquid film. For values of $y^+ > 21$, the disturbance increases with y^+ to the limit of the conditions at $y^+ = 80$.

Heat-transfer results. - The previous analysis was applied to film-cooling heat-transfer results, reported in reference 1 and shown reproduced in figure 8, where cooling effectiveness is shown as a function of water flow for three different hot-gas-stream conditions. Values of the flow-rate parameter w^+ were determined for water flows representing medians over which marked changes in cooling effectiveness occurred, which were suspected to correspond to the initial occurrence of liquid-film disturbances. The viscosity of water at 210° F (estimated average temperature of water film) was used. The corresponding values of y^+ as plotted on figure 6 varied between 34 and 46, which are higher values than obtained for the transition region from the visual observations. This result would be expected because of the differences in the two systems. The visual results were obtained with ambient gas-stream temperature; thus no evaporation of the liquid into the gas stream occurred, and the thickness of the liquid film was essentially constant downstream of the injection point. In the heat-transfer investigations, however, liquid was evaporating from the liquid film and the thickness decreased along the duct. Thus the two systems can be compared only at a point where, in the heat-transfer case, no liquid has been lost to the gas stream, which would be the injection point. For the visual observations where the thickness is constant along the duct, when the initial thickness of the liquid film is sufficient for surface disturbances to occur, the disturbances occur along the entire duct. In the heat-transfer investigations, however, the thickness decreases along the duct and this decrease would tend to stabilize any disturbances of the film surface. Thus for the same value of y^+ and the same initial liquid flow, the liquid-film surface would be more turbulent in the visual observations than in the heat-transfer investigations. By assuming the average thickness of the liquid film to be one-half the initial thickness for the heat-transfer case, the determined value of y^+ is reduced by a factor of 2 (from that for no evaporation) and the heat-transfer results are in agreement with the visual results.

The approximate liquid flow at which the surface disturbances initially occur can be obtained using a flow-rate parameter w^+ of 90, which corresponds to $y^+ = 15$. The approximate liquid flow at which the effectiveness of the liquid changes in a film-cooling application can be obtained by using a flow-rate parameter w^+ of 360, which corresponds to $y^+ = 37$.

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For a liquid film-cooling application, the occurrence of the surface disturbances results in a lower cooling effectiveness of the liquid; hence it would be desirable to eliminate the disturbances, or even delay their occurrence to a higher liquid flow. Because the disturbances are related to a fundamental flow phenomenon previously described, no obvious method of preventing this occurrence at the higher liquid flows is proposed. For a given application it may therefore be desirable to limit the flow of an inert coolant introduced at any single axial position and to introduce it at several axial positions to obtain maximum cooling efficiency.

SUMMARY OF RESULTS

Visual observations and flow analysis were made of annular liquid flow with cocurrent air flow in 2- and 4-inch-diameter horizontal transparent tubes. The investigations were conducted with air mass velocities from 30.6 to 108 pounds per second per square foot, air temperatures of 80° , 475° , and 800° F, and Reynolds numbers from 410,000 to 2,900,000. The liquid flows consisted of water, water-detergent solutions, and aqueous ethylene-glycol solutions at flows from 0.027 to 0.270 pound per second per foot of tube circumference (0.3 to 21 percent of the air flows). The results are summarized as follows:

1. For the range of conditions investigated, the velocity of the liquid-film surface varied from approximately 10 to 35 feet per second with corresponding liquid-film thicknesses of 0.005 to 0.0005 inch.
2. The liquid flow per circumferential length at which liquid-flow disturbances initially occur increased with increased liquid viscosity, increased slightly with decreased liquid surface tension, and did not vary appreciably with changes of air mass velocity.
3. Liquid-flow disturbances had different appearances with different air mass velocities, liquid viscosities, and liquid surface tensions; in general, the size and the number of disturbances varied.

4. Visual observations at several air temperatures between ambient and 800° F indicated no boiling or appreciable disturbance on the liquid film due to vaporization of the liquid.

CONCLUSIONS

The following conclusions are drawn from the investigations of annular liquid flow with cocurrent gas flow in horizontal tubes:

1. The liquid flow is relatively smooth until the liquid-flow rate is sufficient for the thickness of the liquid annulus to enter the flow region where turbulent forces predominate over viscous forces; disturbances then develop on the liquid film. Approximate liquid-flow rate for this transition can be predicted.
2. For liquid film-cooling applications, the presence of liquid-flow disturbances reduces the cooling effectiveness of the liquid because of higher heat transfer between gas and liquid and loss of liquid to the hot gas stream.
3. The elimination of the liquid-flow disturbances at high coolant flows does not appear feasible; it may thus be desirable in a liquid film-cooling application with inert coolant to limit the amount of coolant introduced at a single axial position and to introduce it at several axial positions.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

D inside diameter of tube, ft

g acceleration due to gravity, 32.2 ft/sec^2

L length of liquid-cooled tube, ft

p static pressure, lb/sq ft absolute

u velocity parallel to axis of tube, ft/sec

u_b bulk or average velocity at cross section of tube, ft/sec

W flow rate, lb/sec

w flow rate per unit length, lb/sec/ft

x axial distance from liquid injector, ft

y distance from tube wall, ft

μ_o absolute viscosity of fluid at wall, lb-sec/sq ft

ρ mass density, $\text{lb-sec}^2/\text{ft}^4$

ρ_b bulk or average density at cross section of tube, $\text{lb-sec}^2/\text{ft}^4$

ρ_o mass density of fluid at wall, $\text{lb-sec}^2/\text{ft}^4$

τ_o shear stress in fluid at wall, lb/sq ft

Subscripts:

fr on friction pressure gradient

g gas flow

l liquid flow

Dimensionless parameters:

$$f \quad \text{friction factor, } - \frac{D \left(\frac{dp}{dx} \right)_{fr}}{2 \rho_b u_b^2}$$

$$u^+ \quad \text{velocity parameter, } \frac{u}{\sqrt{\tau_0 / \rho_0}}$$

$$y^+ \quad \text{wall-distance parameter, } \frac{\sqrt{\tau_0 / \rho_0}}{\mu_0 / \rho_0} y$$

$$w^+ \quad \text{flow-rate parameter, } \frac{w}{\pi D g \mu_0}$$

APPENDIX B

CALCULATION OF VELOCITY AND THICKNESS OF LIQUID FILM

For annular liquid flow with cocurrent gas flow in a horizontal duct, the velocity or the thickness of the annular liquid film can be calculated using the dimensionless parameters u^+ and y^+ from figure 6, which were obtained from reference 5.

Velocity calculation. - The parameter u^+ is defined as

$$u^+ = \frac{u}{\sqrt{\frac{\tau_o}{\rho_o}}} \quad (B1)$$

The friction velocity $\sqrt{\tau_o/\rho_o}$ for a homogeneous fluid flowing in a duct is given by the equation

$$\sqrt{\tau_o/\rho_o} = u_b \sqrt{f/2} \quad (B2)$$

For annular liquid flow with cocurrent gas flow, however, equation (B2) must be modified. This modification is accomplished by referring the friction velocity $\sqrt{\tau_o/\rho_o}$ to the liquid annulus and by considering the gas flow to be replaced by a fictitious flow of the same liquid as in the annulus. Then the restriction is imposed that the pressure drop per unit length must be the same for the fictitious liquid flow as for the gas flow with the friction factor f for the actual conditions applying to each case. This restriction means that the dynamic pressures of the fictitious liquid flow and gas flow must be equal or

$$u_{b,l} = \sqrt{\frac{\rho_{b,g}}{\rho_{b,l}}} u_{b,g}$$

Substituting for the velocity in equation (B2) and combining the result with equation (B1) give the following relation for the liquid-surface velocity:

$$u_l = u^+ l \sqrt{\frac{f}{2}} \sqrt{\frac{\rho_{b,g}}{\rho_{b,l}}} u_{b,g} \quad (B3)$$

Thickness calculation. - The parameter y^+ is defined as

$$y^+ = \frac{\sqrt{\tau_o/\rho_o}}{\mu_o/\rho_o} y$$

Again, referring the expression for y^+ to the liquid annulus and expressing the friction velocity $\sqrt{\tau_o/\rho_o}$ in terms of the gas-stream velocity give the following relation for the liquid-film thickness:

$$y_l = y^+ \sqrt{\frac{\mu_{o,l}}{\rho_{o,l}}} \sqrt{\frac{2}{f}} \sqrt{\frac{\rho_{b,l}}{\rho_{b,g}}} \frac{1}{u_{b,g}} \quad (B4)$$

All of the variables appearing in equations (B3) and (B4) except the friction factor are known for any given conditions. The friction factor for annular liquid flow with cocurrent gas flow is unavailable from experimental data for the range of conditions investigated in this report. Extrapolation of the data in references 2 and 3 indicates that the friction factor for the conditions reported herein is in the order of two to four times that of single-phase flow in a smooth duct for the same gas-stream Reynolds number.

For convenience, a flow-rate parameter defined as $w^+ = W_l / \pi D g \mu_o$ (appendix C) is used for the calculations. It is the integral of the curve of figure 6 and is plotted as a function of y^+ in figure 7.

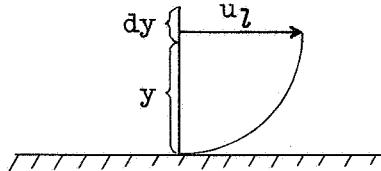
Calculation procedure. - The following procedure is used to determine the velocity and the thickness of the annular liquid film.

1. Determine the value of the flow-rate parameter $\frac{W_l}{\pi D g \mu_o}$.
2. Using this value, employ figure 7 to obtain the corresponding value of y^+_l .
3. The corresponding value of u^+_l is then obtained from figure 6.
4. The velocity or the thickness of the liquid film can then be determined from equation (B3) or (B4), respectively.

APPENDIX C

DERIVATION OF FLOW-RATE PARAMETER

Consider the continuity equation in the region near the wall where a velocity gradient is present:



The flow rate per unit width w_l through the element dy is given by the relation

$$dw_l = g \rho u_l dy \quad (C1)$$

Substituting the dimensionless parameters u^+ and y^+ , which are defined as

$$u^+ = \frac{u}{\sqrt{\tau_0/\rho_0}}$$

$$y^+ = \frac{\sqrt{\tau_0/\rho_0}}{\mu_0/\rho_0} y$$

in equation (C1) and assuming a constant density across the liquid film give the relation

$$\int_0^{w_l} dw_l = g \mu_0 \int_0^{y^+} u^+ dy^+$$

Thus

$$\frac{w_l}{g \mu_0} = \int_0^{y^+} u^+ dy^+ \quad (C2)$$

The flow rate per unit width w_l can be approximated for a circular duct by dividing the total liquid-flow rate W_l by the circumference of the duct. A flow-rate parameter w^+ is thus obtained from equation (C2) as

$$w^+ = \frac{W_l}{\pi D g \mu_0} = \int_0^{y^+} u^+ dy^+ \quad (C3)$$

The value of $\int_0^{y^+} u^+ dy^+$ can be evaluated for any desired value of y^+ by graphical integration of the curve of figure 6. The result of this graphical integration for various values of y^+ is shown in figure 7.

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TABLE I - EFFECT OF AIR MASS VELOCITY, TUBE SURFACE, AND
TUBE DIAMETER ON LIQUID-FLOW TRANSITION REGION

[Conditions: liquid, water; air temperature, 80° F]

Air mass velocity (lb/(sec)(sq ft))	Liquid-flow transition region ^a (lb/(sec)(ft))		
	Pyrex tube		Lucite tube
	4 inch	4 inch	2 inch
30.6	0.052-0.063	0.035-0.065	0.037-0.060
44.5	.052- .068	.040- .068	.038- .063
70.0	.050- .068	.037- .073	.038- .062
108	.048- .068	.035- .070	.038- .062

^aFrom visual observations.

TABLE II - EFFECT OF LIQUID SURFACE TENSION ON LIQUID-FLOW
TRANSITION REGION

[Conditions: tube, pyrex; air mass velocity,
44.5 lb/sec/sq ft; air temperature, 80° F]

Liquid (percent by weight detergent in water)	Absolute viscosity at 80° F (lb-sec)/(sq ft)	Surface tension at 80° F (dynes/cm)	Liquid-flow transition region ^a (lb/(sec)(ft))
0.000	1.84×10^{-5}	72	0.052-0.068
.004	1.84	55	.057- .082
.025	1.84	45	.063- .090
.050	1.84	41	.067- .090
.095	2.05	36	.063- .097
.150	2.07	33	Not determined

^aFrom visual observations.



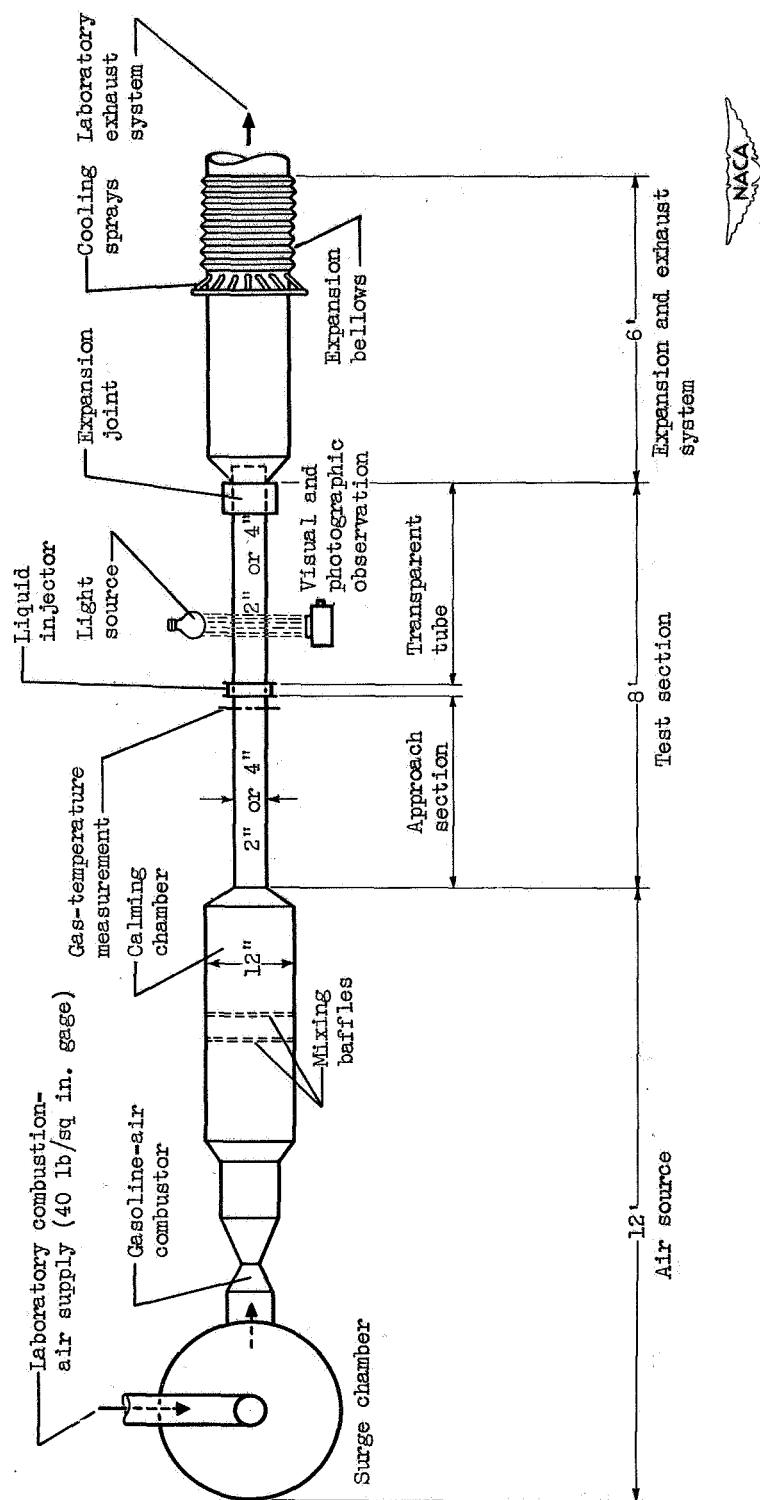
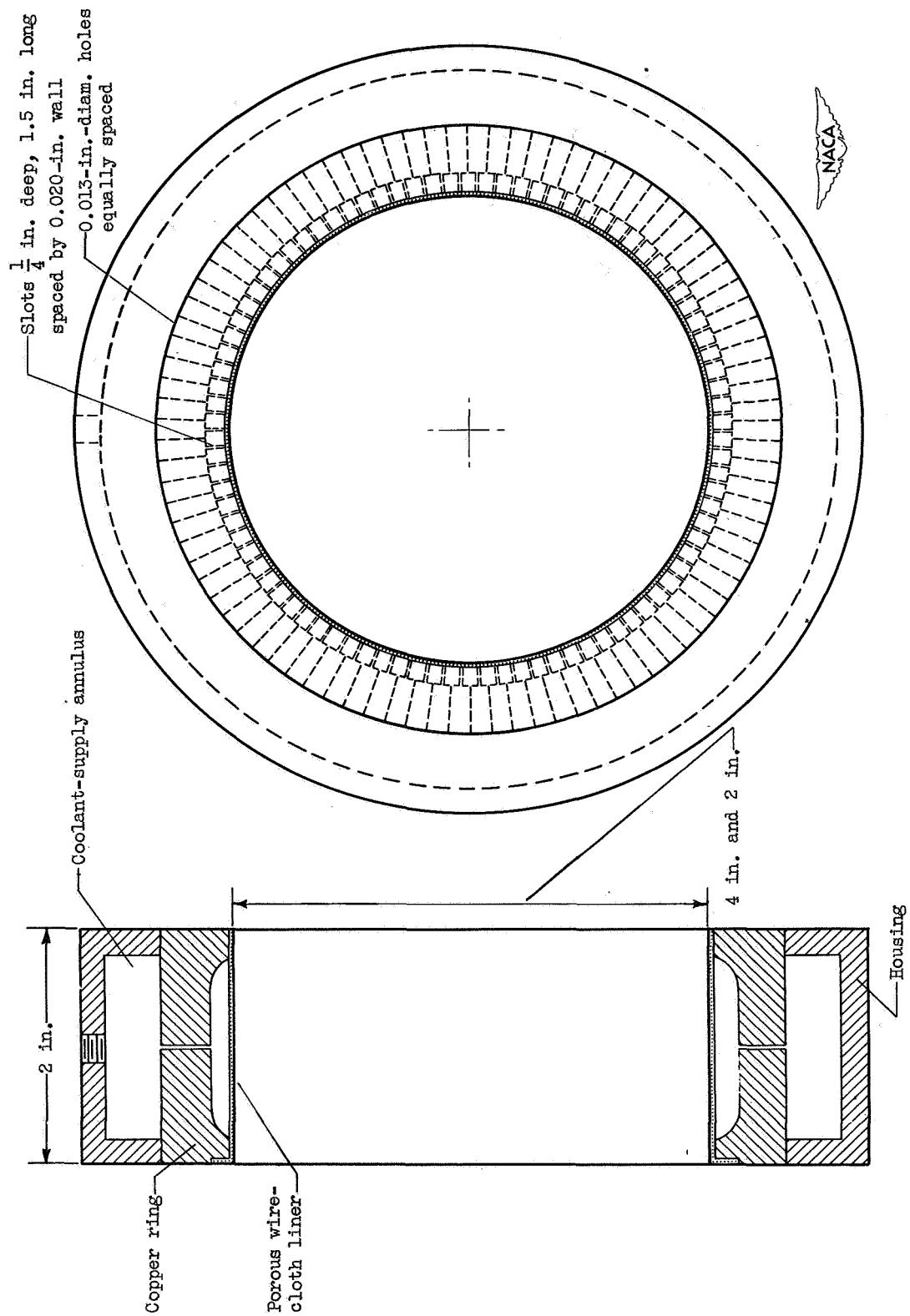
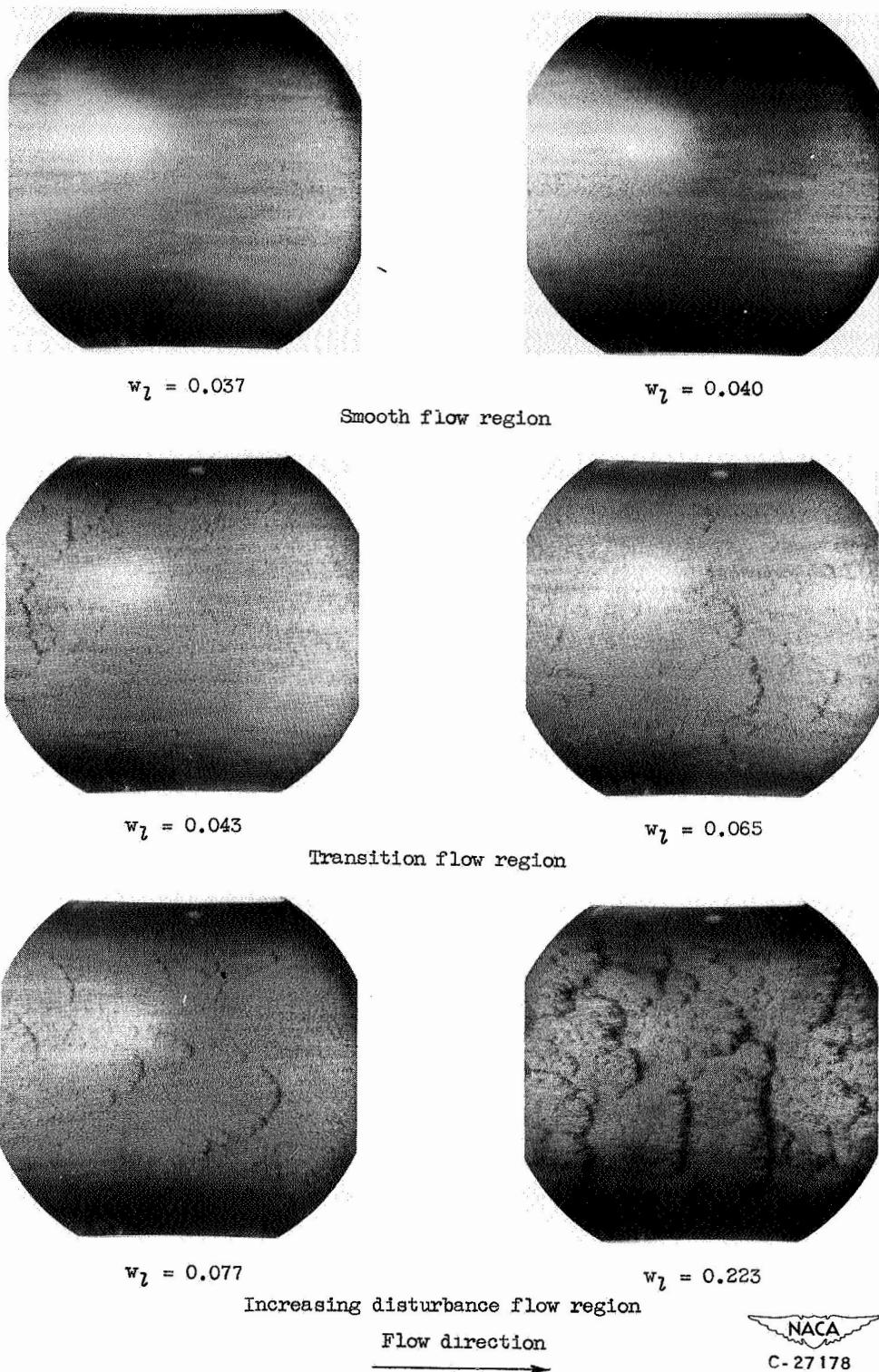


Figure 1. - Flow system.

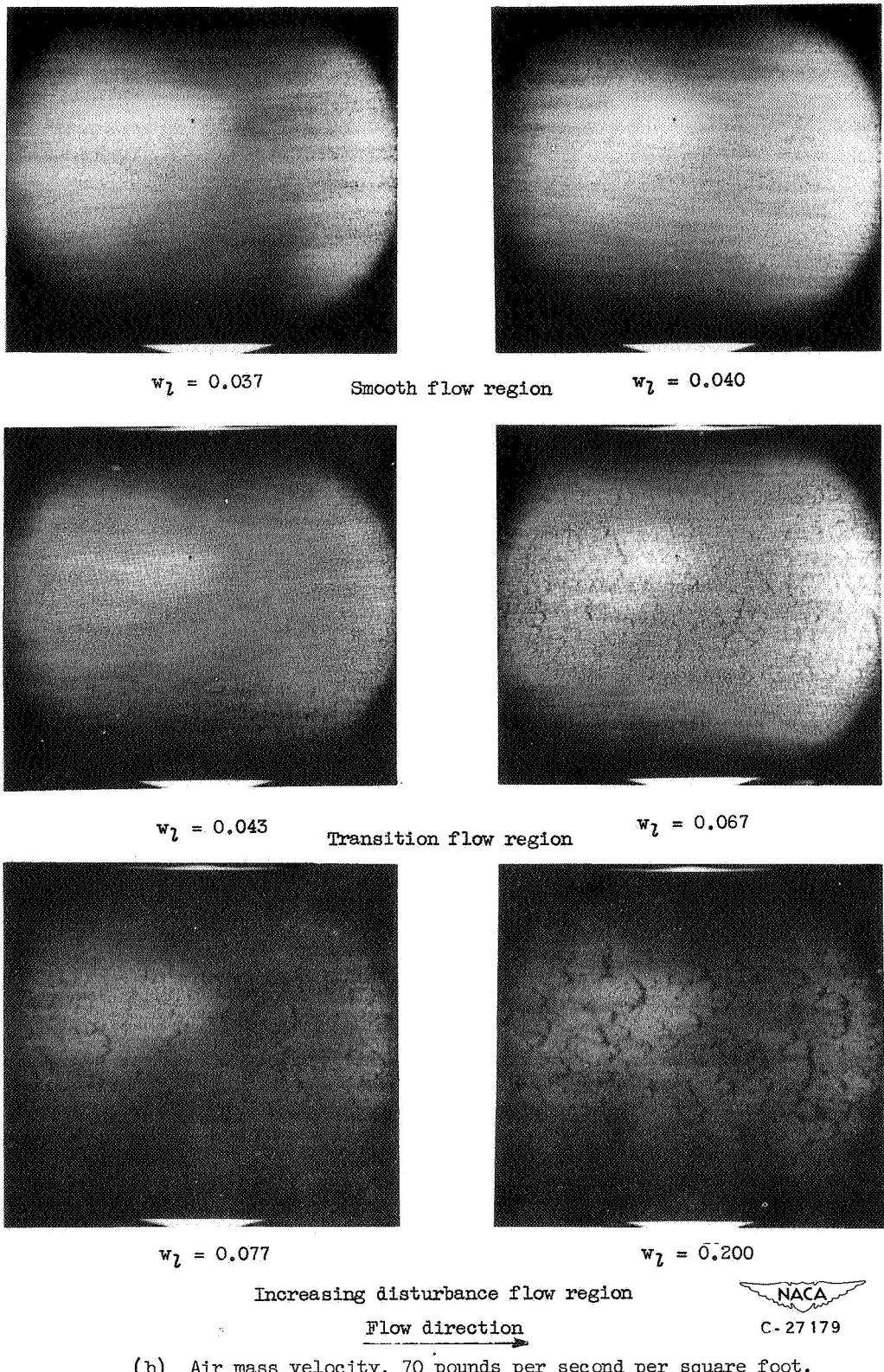




(a) Air mass velocity, 44.5 pounds per second per square foot.

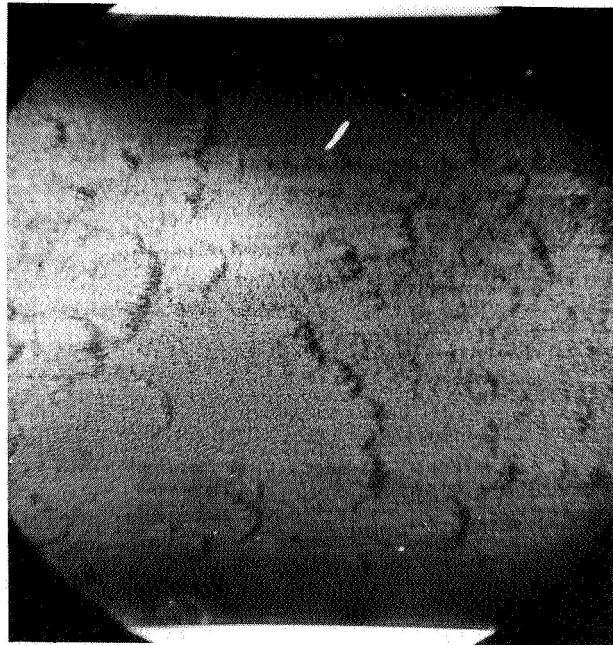
Figure 3. - Shadowgraph pictures of annular water flow with cocurrent air flow in horizontal tube. Air temperature, 80° F; Lucite tube diameter, 4 inches; liquid flow, w_l , pounds per second per foot of circumference.

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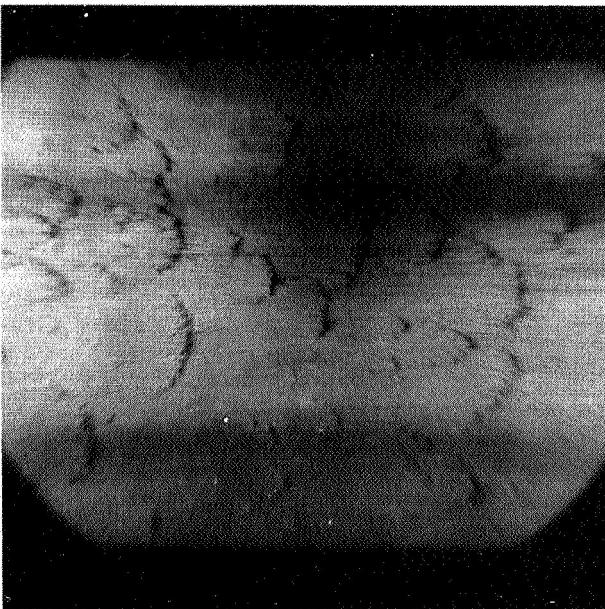


(b) Air mass velocity, 70 pounds per second per square foot.

Figure 3. - Concluded. Shadowgraph pictures of annular water flow with cocurrent air flow in horizontal tube. Air temperature, 80° F; Lucite tube diameter, 4 inches; liquid flow, w_l , pounds per second per foot of circumference.



(a) Air temperature, 80° F; water flow, 0.093 pound per second per foot; Lucite tube diameter, 4 inches.



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(b) Air temperature, 800° F; water flow, 0.130 pound per second per foot; pyrex tube diameter, 4 inches.

Figure 4. - Shadowgraph pictures of annular water flow with cocurrent air flow in horizontal tube at different air temperatures. Air mass velocity, 44.5 pounds per second per square foot.

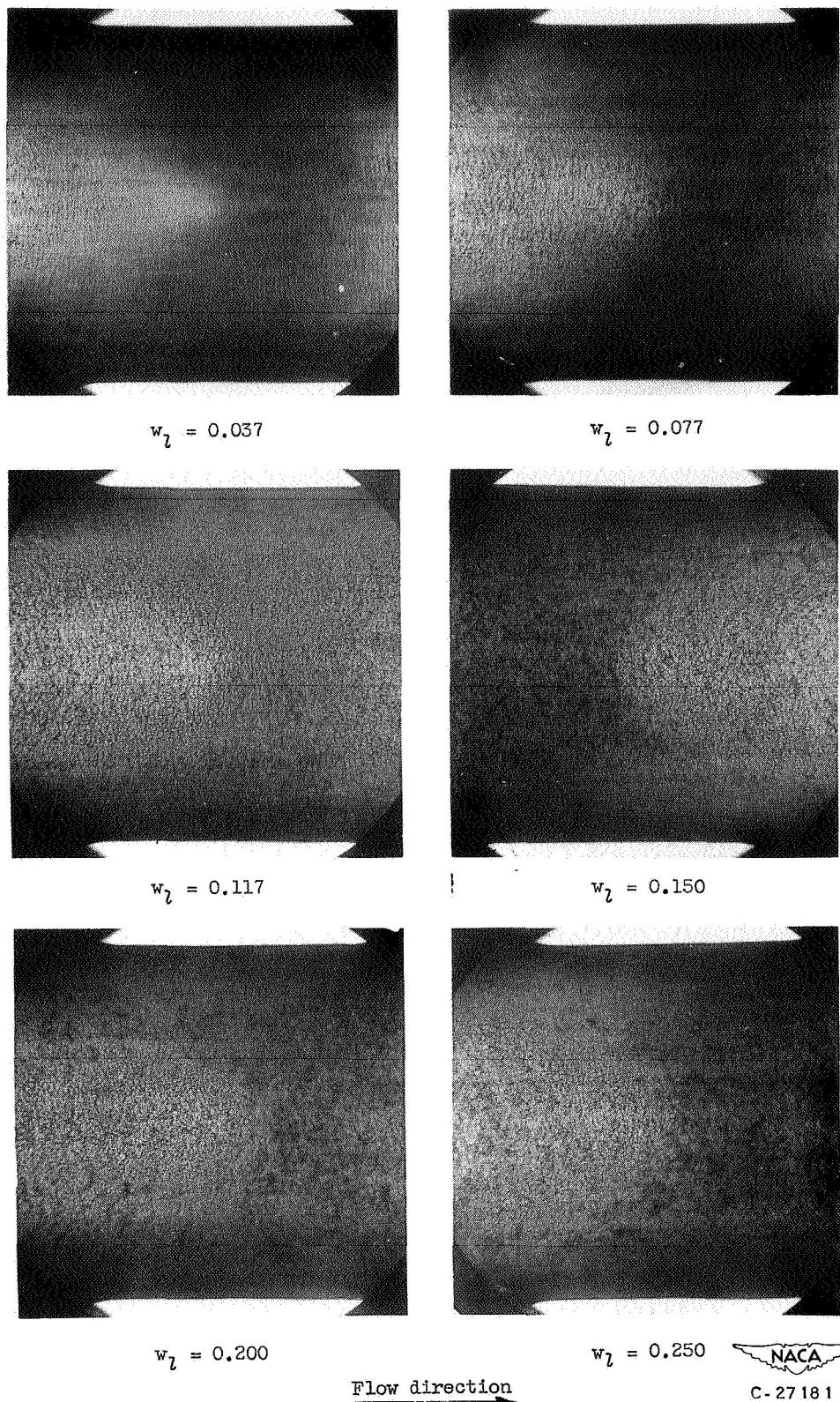


Figure 5. - Shadowgraph pictures of annular liquid flow of 53-percent glycol-water solution with cocurrent air flow in horizontal tube. Air mass velocity, 44.5 pounds per second per square foot; air temperature, 80° F; Lucite tube diameter, 4 inches; liquid flow, w_l , pounds per second per foot of circumference.

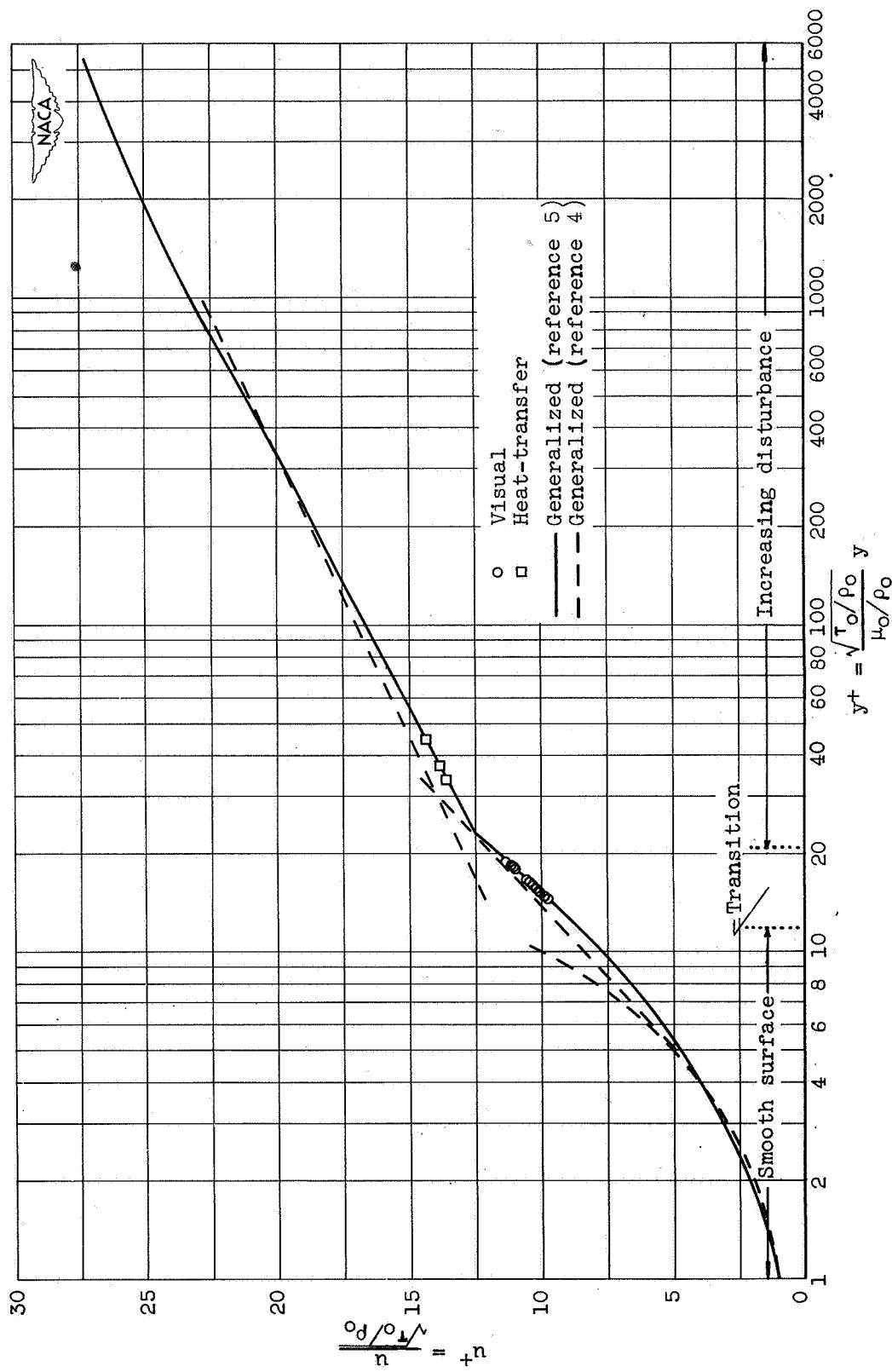


Figure 6. - Association of visual flow regions and heat-transfer results with generalized velocity distribution for fully developed flow in smooth tubes applied to liquid films.

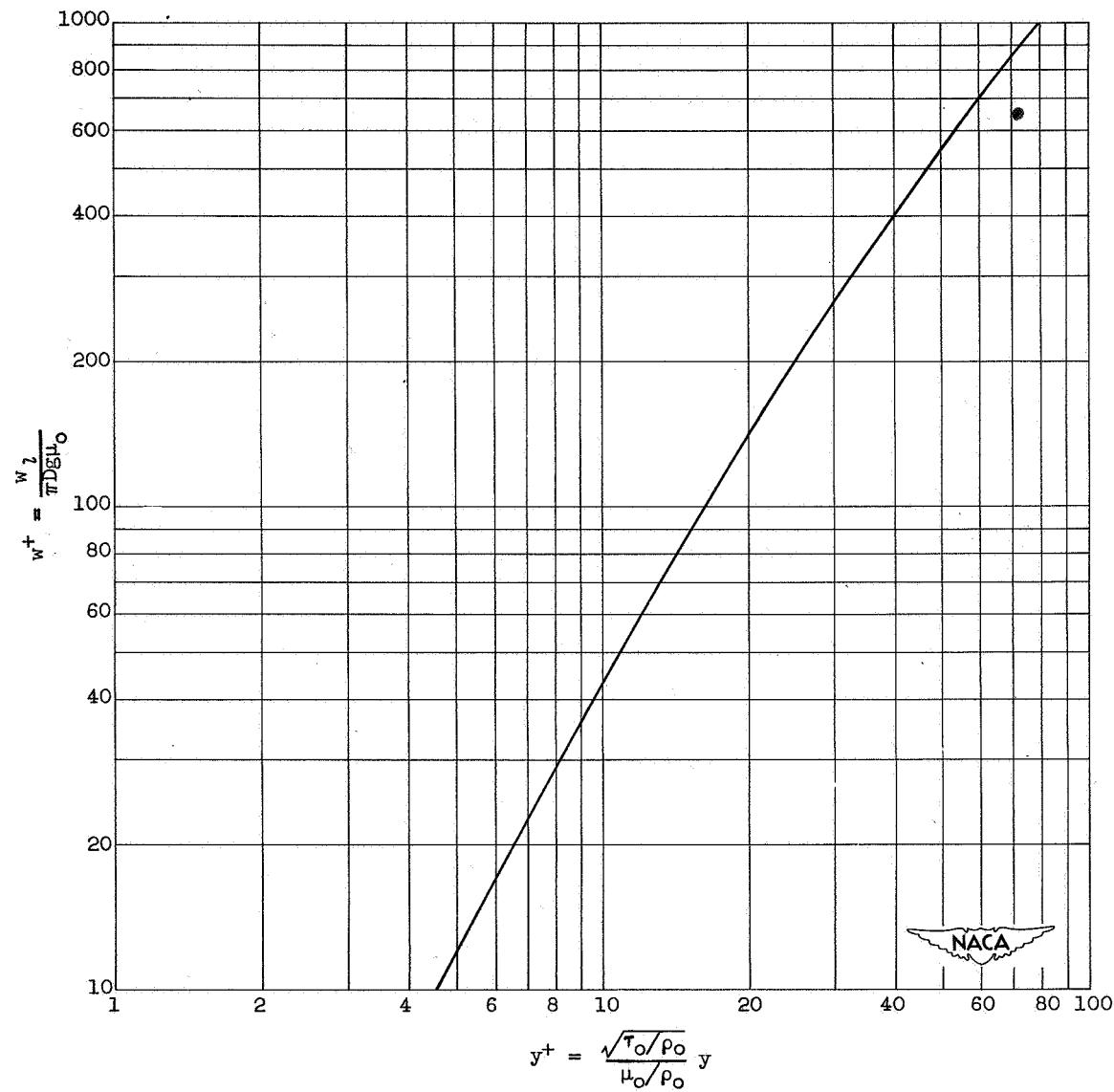


Figure 7. - Variation of dimensionless flow-rate parameter with wall-distance parameter.

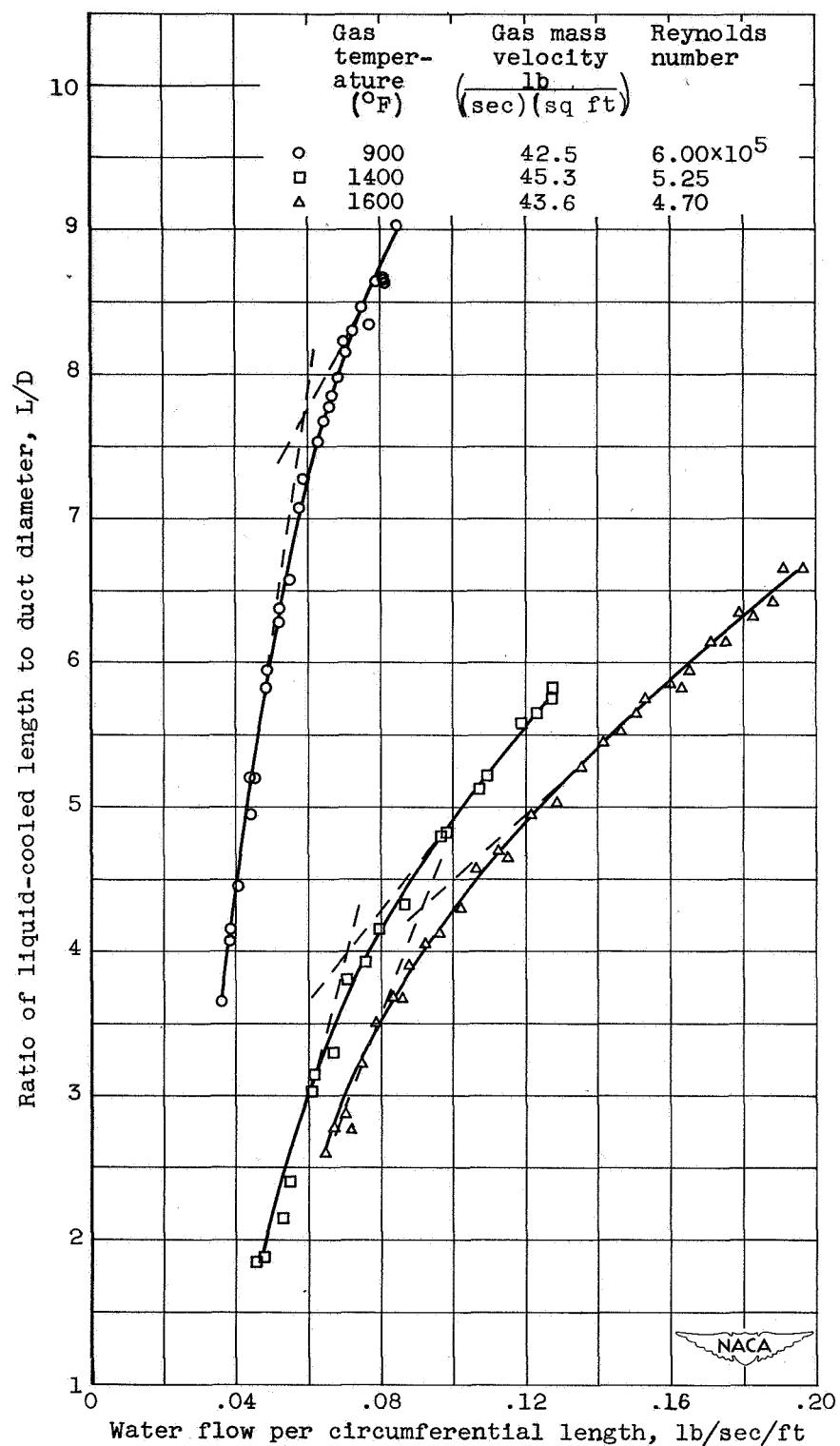


Figure 8. - Variation of liquid-cooled length with water flow per unit circumference using smooth-surface duct (reference 1).